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Infiltration of Ambient $PM_{2.5}$ through Building Envelope in Apartment Housing Units in Korea

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ABSTRACT

Air pollution due to $PM_{2.5}$ is of public concern in Korea. Ambient $PM_{2.5}$ can penetrate indoors through the building envelope, affecting the indoor $PM_{2.5}$ concentrations. Most people stay indoors for approximately 80% of every day, implying that their primary exposure to $PM_{2.5}$ could be determined by the indoor air. This study aims to investigate the infiltration of ambient $PM_{2.5}$ through the building envelop in apartment housing units in Korea. The on-site infiltration test method, by using a blower-door depressurization procedure, was suggested in order to maintain an identical indoor-outdoor pressure difference among the tests. On-site experiments were conducted in 11 apartment housing units to estimate the $PM_{2.5}$ infiltration factors. The results showed that the average infiltration factor of all the test housing units was 0.65 ± 0.13 (average ± standard deviation), with a minimum of 0.38 and a maximum of 0.88. Furthermore, the results from the relation of the building airtightness data to the infiltration factors suggests that a leaky housing unit with high ACH_{50}, or a high specific effective leakage area (ELA), would be more significantly influenced by the ambient $PM_{2.5}$. The study demonstrated that the suggested infiltration test procedure was useful to assess the infiltration factors in conditions of controlled indoor-outdoor pressure differences in real housing units.

Keywords: $PM_{2.5}$; Infiltration; Building envelope; Apartment housing unit; Indoor air quality; Blower-door testing.

INTRODUCTION

Particulate matter (PM) pollution is considered a major threat, as it is associated with detrimental effects on human health and the quality of life (Stanek *et al.*, 2011; Henschel *et al.*, 2012; Van Erp AM *et al.*, 2012; WHO, 2013). Strong evidence points to the negative effects of short- and long-term exposure to PM on the respiratory and cardiovascular health of humans (Beelen *et al.*, 2008; Samoli *et al.*, 2008). In particular, particles with a diameter of less than 2.5 µm ($PM_{2.5}$) are of high concern because of their adverse effects on the respiratory system (Pope *et al.*, 2009). $PM_{2.5}$ has been used commonly as one of indicators to describe PM. It has been shown that long-term exposure to $PM_{2.5}$ is a strong risk factor for mortality (Pope *et al.*, 2002; Lepeule *et al.*, 2012; WHO, 2013). Air pollution due to $PM_{2.5}$ in Korea is a matter of significant public concern. According to the Organization for Economic Cooperation and Development (OECD), the average annual concentration of the ambient $PM_{2.5}$ levels in Korea is 29.1µg m^{-3} (OECD, 2015), which is the highest among the OECD countries, where the average level is 14.5 µg m^{-3}, and is much higher than is the annual guideline limit of 10 µg m^{-3} set by the World Health Organization (WHO) (WHO, 2006). Ambient $PM_{2.5}$ is known to be associated with industry, urbanization, and transport. This implies that the majority of the population in Korea is exposed to high levels of $PM_{2.5}$, and the attendant health risks, as a high percentage of people live in urban city areas. Moreover, the Asian dust event, called yellow dust, affects the Korean Peninsula during the winter and spring seasons (Kim and Park, 2001). Studies have indicated that increased $PM_{2.5}$ concentrations were observed during such dust events (Kim and Kim, 2001; Stone *et al.*, 2011), exacerbating the already high levels of ambient $PM_{2.5}$.

In view of the growing concerns on ambient PM pollution, the Korea Environment Corporation, an affiliated agency under the Ministry of Environment, has since 2005 been providing real-time $PM_{2.5}$ data online, along with the data on other air pollutants (PM_{10}, O_3, CO, SO_2, No_2). The data on the concentrations of $PM_{2.5}$ are collected from 317 sites in 97 areas across the country and are displayed hourly on the AirKorea website (KECO, 2016). AirKorea advises sensitive groups to stay indoors when the hourly average $PM_{2.5}$ concentration exceeds 90 µg m^{-3} for over two hours. A warning is issued when the value exceeds 180 µg m^{-3} for over two hours, with every person prohibited from going

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outdoors. However, most people stay indoors for about 90% of every day (Jenkins *et al.*, 1992; Robinson and Nelson, 1995; McCurdy *et al.*, 2000; Klepeis *et al.*, 2001; Schweizer *et al.*, 2007), which means that their primary exposure to $PM_{2.5}$ could be determined by the indoor air. Moreover, children and the elderly, especially, probably spend most of their time indoors, particularly in a residential setting. Most of the residential units in Korea rely on natural ventilation, without any filtering system; therefore, closing the windows and doors could be the only solution to counteract the high ambient $PM_{2.5}$ conditions. Nevertheless, ambient $PM_{2.5}$ can penetrate indoors through the building envelope, affecting the indoor $PM_{2.5}$ concentrations (Liu and Nazaroff, 2003).

Numerous studies have been conducted to show the effects of ambient $PM_{2.5}$ on the indoor environment (Baek and Kim, 1997; Adgate *et al.*, 2002; Long and Sarnat, 2004; Cao *et al.*, 2005; Meng *et al.*, 2005). For quantification of the infiltration process through building leakage, three parameters have been used widely, i.e., the indoor/outdoor (I/O) ratio (Monn *et al.*, 1995; Abt *et al.*, 2000; Long and Sarnat, 2004; Lunden *et al.*, 2008), the infiltration factor (Lee *et al.*, 1997; Landis *et al.*, 2001; Wallace and William, 2005; Lazaridis *et al.*, 2006; Sarnat *et al.*, 2006; Hoek *et al.*, 2008; Meng *et al.*, 2009), and the penetration factor (Long *et al.*, 2001; Chao *et al.*, 2003; Thatcher *et al.*, 2003; Zhu *et al.*, 2005). The I/O ratio represents the relationship between the indoor and outdoor PM concentrations. The infiltration factor represents the equilibrium fraction of ambient PM that penetrates indoors and remains suspended in the indoor air. The penetration factor expresses the fraction of the particles in the infiltration air that passes through the building envelope. Although the penetration factor is the most relevant parameter for penetration through the envelope, the infiltration factor can be a useful parameter to analyze the total indoor $PM_{2.5}$ entering from the outdoor environment (Chen and Zhao, 2011). In most previous studies, experiments have been conducted relevant to the infiltration factor in real buildings in natural air exchange conditions. However, differences in wind direction and speed at the time of measurements could cause variations in the indoor-outdoor pressure difference and the air exchange rate, which makes a direct comparison of buildings difficult. Moreover, the urban areas in Asian countries, where high concentrations of $PM_{2.5}$ are of concern, have a high density of high-rise residential buildings, with a wide range of indoor-outdoor pressure differences. Thus, it would be effective to derive the infiltration factor under controlled conditions of indoor-outdoor pressure difference.

The aim of this study was to investigate the infiltration of ambient $PM_{2.5}$ through the building envelop, which affects the indoor air quality in the apartment housing units, by estimating the infiltration factors in controlled indoor-outdoor pressure differences. The on-site infiltration test method, using a blower-door depressurization procedure, was suggested to maintain an identical indoor-outdoor pressure difference among the tests in the different apartment housing units. In addition, the building airtightness was measured to determine the relation between the building airtightness and the infiltration factors.

EXPERIMENTAL METHOD

On-site experiments in 11 apartment housing units in Korea were conducted from December 2015 to April 2016 in order to investigate the infiltration of ambient $PM_{2.5}$ through the building envelope, with the infiltration factors being used as a parameter of the ambient $PM_{2.5}$ infiltration. To estimate the infiltration factors, a test method, using a blower-door depressurization technique, with an identical indoor-outdoor pressure difference of 10 Pa was proposed. The 10 Pa pressure difference was determined to reflect the normal pressure differences applicable to a building envelope (Kalamees *et al.*, 2010). Control of the indoor-outdoor pressure difference facilitates a direct comparison of the estimated infiltration factors among the test housing units. The building airtightness was also measured to obtain leakage information on the test units and to determine the correlation between their airtightness and infiltration factors. The blower-door airtightness test was conducted in compliance with ISO 9972 standard, estimating the air changes per hour at specified pressure, typically 50 Pa (ACH_{50}), and the effective leakage area (ELA) which are widely used airtightness index.

Description of Apartment Housing Units

Eleven unoccupied apartment housing units, located in three cities in Korea, were chosen as test units, as shown in Table 1. The age of the apartment buildings varied from 1

Table 1. Description of test housing units.

Housing unit code	Age (years)	Floor area (m^2)	Ceiling height (m)	Apartment housing unit type	City
A	10	85	2.3	Three bedroom	Daegu
B	19	212	2.3	Four bedroom	Daegu
C	37	57	2.15	Three bedroom	Seoul
D	34	36	2.3	Two Bedroom	Seoul
E	12	85	2.3	Three bedroom	Seoul
F	14	36	2.3	Two bedroom	Seoul
G	4	18	2.3	Studio	Seoul
H	20	50	2.3	Two bedroom	Chungju
I	6	20	2.15	Studio	Seoul
J	14	65	2.25	Three bedroom	Seoul
K	1	36	2.3	Two bedroom	Seoul

to 37 years. The types of housing unit ranged from a studio apartment to one- to four-bedroom apartments, and the floor area of the housing units varied from 18 m^2 to 212 m^2. In general, the north and/or south sides of the housing units were exposed to the outdoor air, and the junctions of the vertical walls and windows were assumed the main particle infiltration passages through the building envelope. The housing units feature different types of windows and window frames, i.e., single pane and double-strength sheet windows. There was no mechanical ventilation system in the units, except a local ventilation system, such as a kitchen hood and bathroom exhaust fan.

Envelope Airtightness Testing

Envelope airtightness was measured by using the typical blower-door fan depressurization/pressurization technique (Retrotec 3101 Blower Door System, Retrotec, USA). This technique measures the air flow through the building envelope leaks at indoor-outdoor pressure differences, which can be expressed by a power-law equation of flow through an orifice, as shown in Eq. (1).

$$Q_f = C\Delta P_f^n \quad (1)$$

where, Q is the air flow (m^3 h^{-1}), ΔP is the pressure difference (Pa), C is the flow coefficient (m^3 h^{-1} Pa^{-n}), n is the pressure exponent, and the subscript f relates to the fan-induced flow or pressure. The constants C and n are obtained by regression of the data derived from the blower-door testing.

The aim of the testing is to characterize the airtightness of the test units by estimating the ACH_{50} and the ELA (ISO 9972, 2015). The specified pressure ACH_{50} facilitates a comparison of the normalized airflow of the test units with a different volume induced by pressure of 50 Pa with the use of a fan. The absolute size of the leakage in the units is quantified by ELA, defined by Eq. (2).

$$\mathrm{ELA} = C \cdot \Delta P_r^{n-1/2} \cdot \sqrt{\frac{\rho}{2}} \quad (2)$$

where ELA is the effective leakage area (m^2), ΔP_r is the reference pressure, and ρ is the density of the air (kg m^{-3}). The C and n values were determined from the blower-door testing results by fitting Eq. (1). The air flow through the building envelope leaks was measured relevant to five-point indoor-outdoor pressure differences (10, 20, 30, 40, 50 Pa). The specific leakage area, defined by the ratio of the effective leakage area to the floor area of the unit, was used to compare the relative leakiness of units of different sizes.

As regards the envelope airtightness testing, the front entrance of each unit was selected as the doorway to install the blower-door system. Before each test, the exterior doors and windows were closed and locked, remaining shut during the test. All the interior doors were opened and the kitchen hood and bathroom exhaust fan were turned off and sealed. In addition, all other possible leakage pathways, i.e., wall outlets and bathroom drains were sealed.

Test Procedure for Infiltration Factors of $PM_{2.5}$

Fig. 1 shows the schematic diagram of the test procedure. Maintaining an identical indoor-outdoor pressure difference during the experiments could be achieved by using the blower-door depressurization procedure. Before the main infiltration test procedure, a blower door was installed at the front entrance of each test unit and, simultaneously, two identical $PM_{2.5}$ concentration monitors (TSI AM 510, TSI, USA) were installed both indoors and outdoors. Both $PM_{2.5}$ monitors were calibrated and certified by the manufacturer right before the experiments for the quality assurance of the measurements. A recent research (Yun *et al.*, 2015) demonstrated that the monitors require correction to measure the mass of particulates and suggested the correction factor of AM510 in Korean situation. In this study, to focus on the investigation of the infiltration factors by measuring ratios between indoor-outdoor particle concentrations, the correction of the monitors was not considered. The indoor $PM_{2.5}$ sampling location was a table located in the center of every housing unit. Typically, Korean apartment housing units are equipped with a packaged air conditioner, with an outdoor condenser unit located on the vertical wall outside each unit. The outdoor $PM_{2.5}$ monitor was placed on the outdoor condenser unit. Prior to the blower-door depressurization procedure, all the air pathways, including the kitchen hoods, bathroom exhausts, bathroom drains, and wall outlets were sealed. This sealing was done to ensure that only particle infiltration through the building envelope would be considered in the infiltration test.

The main infiltration test started after the preparations had been completed, with the blower door starting the depressurization (ΔP = 10 Pa) and the $PM_{2.5}$ monitoring devices starting the data logging. The assumption was that the

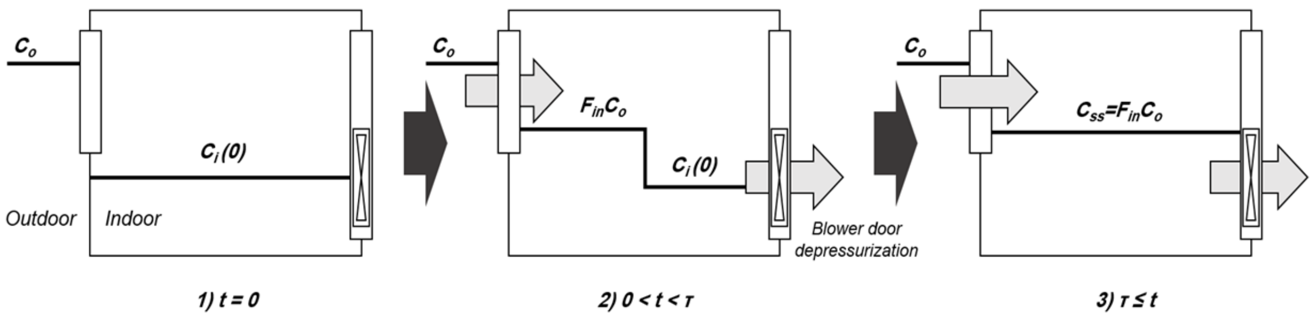

Fig. 1. Schematic diagram of the infiltration test procedure.

infiltrated outdoor air would completely replace the stagnant room air after one time constant. The depressurization was therefore continued for more than one time constant in the test housing units. The time constant was determined by the following Eq. (3).

$$\tau = 1/ACH_{10} \quad (3)$$

where, τ is the time constant (h), and ACH_{10} is the air exchange rate at an indoor-outdoor pressure difference of 10 Pa (h^{-1}). The ACH_{10} value was obtained by the airtightness test.

After one time constant, the indoor $PM_{2.5}$ concentration profile was assumed to have reached steady-state conditions. The blower-door depressurization and the $PM_{2.5}$ monitors remained operating for an additional 20 minutes to record the steady-state indoor and outdoor concentrations. Finally, the recorded $PM_{2.5}$ concentration data were collected for post data analysis to calculate the $PM_{2.5}$ infiltration factors.

The infiltration factors were calculated based on the assumption of the $PM_{2.5}$ mass balance in the housing unit. Assuming there was no indoor $PM_{2.5}$ generation or resuspension, the mass balance equation can be expressed as follows, by Eq. (4).

$$\frac{dC_i(t)}{dt} = \mathrm{P} \cdot \mathrm{ACH}_{10} \cdot C_o - (\mathrm{ACH}_{10} + k) \cdot C_i(t) \quad (4)$$

where, t is the time (h), $C_i(t)$ is the indoor $PM_{2.5}$ concentration at time t, P is the penetration coefficient (-), C_o is the ambient $PM_{2.5}$ concentration, and k is the depositional rate (-).

Several assumptions were made for the infiltration calculation; 1) the ambient $PM_{2.5}$ concentration is constant during the test period, 2) the indoor air in the housing units is well-mixed, and 3) the indoor $PM_{2.5}$ concentration reached equilibrium after one time constant. When the test time is greater than the time constant, it is implied that the indoor $PM_{2.5}$ concentration has reached a steady-state condition, then

$$\frac{dC_i(t)}{dt} = 0 \quad (5)$$

Therefore, Eq. (4) can be summarized as follows by Eq. (6).

$$C_i(t) = C_{i,ss} = \frac{\mathrm{P} \cdot ACH_{10} \cdot C_{o,ss}}{ACH_{10} + k} \quad (6)$$

where, $C_{i,ss}$ is the steady-state indoor $PM_{2.5}$ concentration. Finally, the infiltration factor can be obtained from Eq. (7).

$$F_{in} = \frac{P \cdot ACH_{10}}{ACH_{10} + k} = \frac{C_{i,ss}}{C_{o,ss}} \quad (7)$$

where F_{in} is the infiltration factor (-).

RESULTS AND DISCUSSION

Ambient $PM_{2.5}$ Concentration

Fig. 2 shows the average and the standard deviation of the ambient $PM_{2.5}$ concentrations during the entire test period in each test housing unit. As each test was conducted separately, at different times and locations, there were significant differences in the $PM_{2.5}$ concentrations between the test units. The maximum ambient $PM_{2.5}$ concentration was 180 µg m^{-3} in housing unit H, whereas the minimum concentration was 38 µg m^{-3} in housing unit G. According to the AirKorea website, which provides real-time $PM_{2.5}$ concentration data

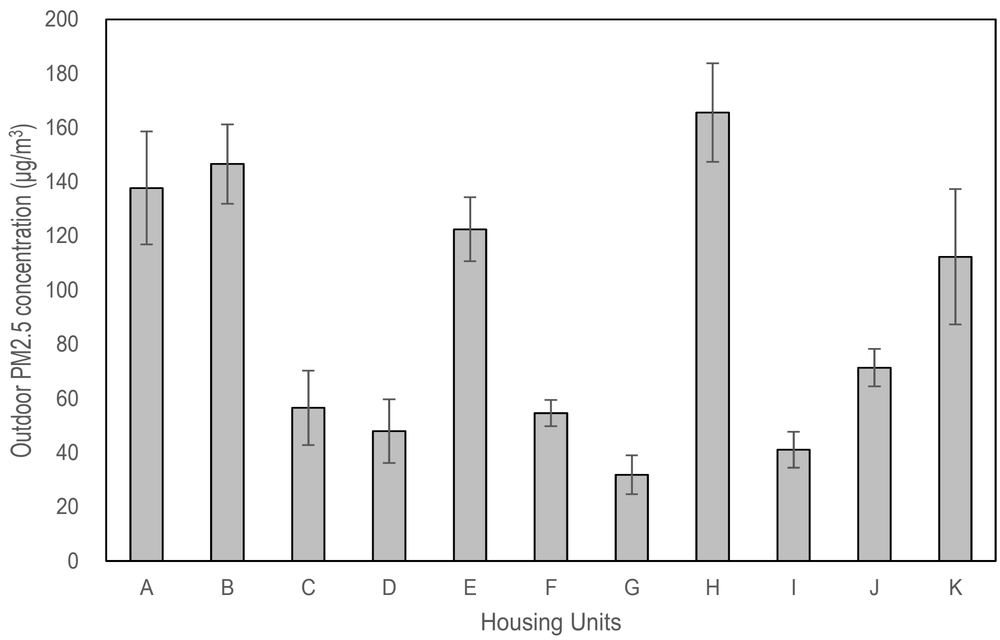

Fig. 2. Average and standard deviation of ambient $PM_{2.5}$ concentration on the day of testing for each unit.

online, the $PM_{2.5}$ concentrations are classified into four categories; good (0–15 µg m^{-3}), average (16–50 µg m^{-3}), bad (51–100 µg m^{-3}), and very bad (more than 100 µg m^{-3}). According to this classification, the measurements indicated that five test housing units had very bad $PM_{2.5}$ concentrations (Units A, B, E, H, and K), three had bad conditions (Units C, F, and J), three had average conditions (Units D, G, and I), with no good conditions being found in any of the housing units.

In all the units, the air quality standard of 35 µg m^{-3} for 24-hour $PM_{2.5}$, established by the United States Environmental Protection Agency (USEPA, 2012), was exceeded. Furthermore, the WHO standard of 10 µg m^{-3} for 24-hour $PM_{2.5}$ was exceeded by a considerable margin (WHO, 2006). Considering that the duration of each test was about five hours, the average ambient $PM_{2.5}$ concentrations presented here are approximately five-hour averaged concentration data. Although no precise direct comparison with the above standards could be made, it could be stated that the levels of the ambient $PM_{2.5}$ concentrations at the time of measurement were relatively high. Compared with the other $PM_{2.5}$ data obtained in Korea, the $PM_{2.5}$ concentration measured in Gosan (Stone *et al.*, 2011) during the spring of 2007 showed similar levels, ranging from 28 to 122 µg m^{-3}, with the 24-h average $PM_{2.5}$ concentration being 36 ± 26 µg m^{-3}. As could be expected, periods with no dust events showed lower levels, while periods with dust events presented higher levels, exceeding 100 µg m^{-3} (Stone *et al.*, 2011).

Airtightness Test Result

Table 2 shows the results of the airtightness tests on the housing units, including the ACH_{50} and ELA. The estimated airtightness test results represent the information on leakage relevant to the exterior vertical walls and the windows of the housing units. The ACH_{50} values of the housing units ranged from 1.44 h^{-1} to 12.39 h^{-1}, which far exceeded the *Passivhaus* standard of 0.6 ACH_{50} (PHI, 2007). Various units (Units A, B, E, G, and K) met the requirement of 5.0 ACH_{50} set by Energy Star 3.0 (USEPA, 2013), while the rest of the units (Units C, D, F, H, I, and J) showed high levels, above 5.0 ACH_{50}. Except for Unit I, the buildings in the group of leaky housing units (Units C, D, F, H, and J) were older than 14 years. Generally, the results showed that the older housing units had poor airtightness, resulting in high ACH_{50} values.

The ELA of the housing units ranged from 8.44 cm^2 to 435.35 cm^2, generally showing a proportional relationship to the floor area. An exceptionally small ELA value of 8.44 cm^2 was indicated for Unit G. This is ascribed to Unit G being recently built, i.e., within a year prior to the tests, having an airtight window system, and being a studio apartment, with the smallest floor area of the all the units.

Usually, the flow exponent depends on the flow regime, namely, 0.5 for fully turbulent flow and 1.0 for laminar flow. In practice in many instances, flow exponent values of approximately 0.6 and 0.7 are found. Generally, in this study, the estimated flow exponent values were found to be within reasonable ranges.

Infiltration Factors of the Test Housing Units

Fig. 3 shows an example of the ambient and indoor $PM_{2.5}$ concentration profile during the infiltration tests to demonstrate the data used to calculate the infiltration factors. The indoor and outdoor concentrations at a steady-state condition were averaged, then listed in Table 3 for all housing units. The infiltration factors were calculated by using the ratios of the steady-state ambient and indoor $PM_{2.5}$ concentrations.

Fig. 4 shows the estimated $PM_{2.5}$ infiltration factors relevant to 10 Pa of pressure difference. The average infiltration factor in all the test housing units was 0.65 ± 0.13 (average ± standard deviation), with a minimum of 0.38 to a maximum of 0.88. Table 3 lists the infiltration factors, as well as the outdoor air exchange rates and the average steady-state ambient $PM_{2.5}$ concentrations of the housing units. Small standard deviation values were indicated for the infiltration factors and average ambient $PM_{2.5}$ concentrations, indicating that the infiltration tests were conducted in sufficiently steady-state conditions.

In their research, Chen and Zhao (2011) reviewed 21 previous experimental studies on the relationship between indoor and outdoor particles, suggesting that the average infiltration factors for $PM_{2.5}$ measured by the different researchers varied considerably between 0.3 and 0.82. The reported experimental data were obtained from homes in the USA or Europe. Compared with the values from previous research, the average infiltration factor of 0.65 measured in

Table 2. Airtightness test results of housing units.

Housing unit code	ACH_{50} (h^{-1})	Effective Leakage Area, ELA (cm^2)	C (m^3 h^{-1} Pa^{-n})	n (-)
A	3.11	130.72	49.11	0.654
B	4.04	435.35	159.63	0.671
C	12.39	381.39	136.02	0.691
D	7.50	144.32	58.31	0.601
E	4.15	191.01	70.82	0.663
F	9.80	199.74	81.94	0.590
G	1.44	8.44	2.53	0.815
H	11.74	342.67	144.13	0.572
I	10.25	97.85	38.24	0.625
J	5.46	212.10	89.15	0.573
K	3.13	43.70	14.60	0.738

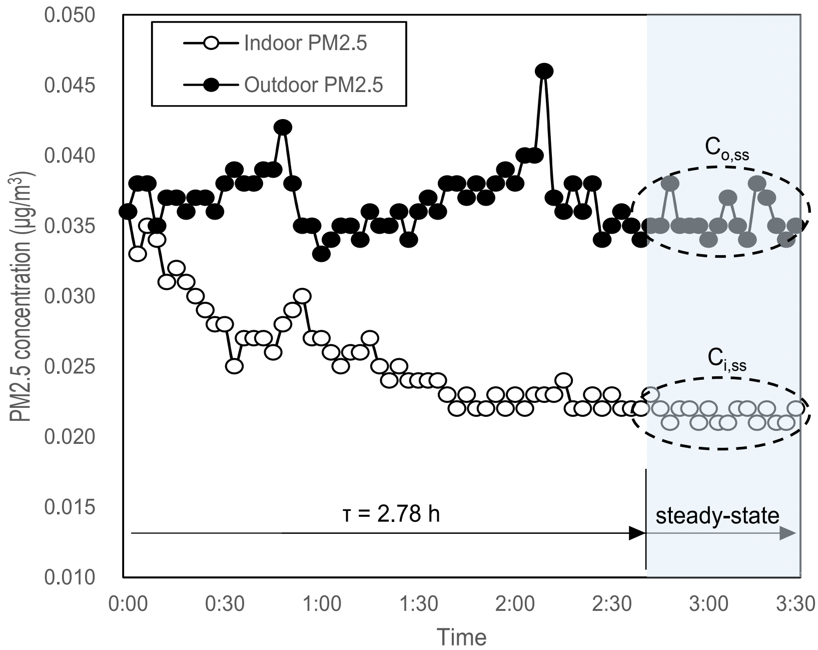

Fig. 3. An example of ambient and indoor $PM_{2.5}$ concentration profile during the infiltration test (Unit G).

Table 3. Results of infiltration tests in test housing units.

Housing unit code	Outdoor air exchange rate, λ (h^{-1})	Indoor $PM_{2.5}$ concentration at steady-state condition, $C_{i,ss}$ (μg m^{-3})		Ambient $PM_{2.5}$ concentration at steady-state condition, $C_{o,ss}$ (μg m^{-3})		Infiltration factors, F_{in} (-)	
		Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
A	1.13	61	0	160	12	0.38	0.03
B	1.45	107	1	168	6	0.64	0.02
C	5.30	56	2	78	2	0.72	0.03
D	2.82	25	0	34	2	0.75	0.04
E	1.00	79	2	134	2	0.59	0.02
F	3.75	38	1	53	1	0.72	0.03
G	0.36	21	1	36	2	0.60	0.03
H	4.89	135	1	192	2	0.71	0.01
I	3.98	31	1	35	2	0.88	0.06
J	2.24	46	1	70	2	0.66	0.02
K	0.98	70	1	131	2	0.53	0.01

the current study in Korea was high. The infiltration factor is a function of particle size, indoor-outdoor pressure difference, air exchange rate, geometry of leaks, and the depositional rate. It is assumed that the 10 Pa indoor-outdoor difference adopted in this study could have affected the level of the infiltration factor.

Fig. 5 shows the relationship between the infiltration factors and the airtightness test results. The ACH_{50}, effective leakage area and the specific effective leakage area were correlated with the infiltration factors. Power trend lines were drawn to illustrate the relationship to the measured data. Generally, although the R-square values were less than 0.5, the infiltration factors tended to increase with the ACH_{50} values.

The results from data on the relationship between the building airtightness and the infiltration factors indicate that a leaky housing unit, with high ACH_{50} or high specific ELA, would be influenced more significantly by polluted ambient $PM_{2.5}$. At the present time, air-tight building construction practices are followed in Korea in the effort to reduce energy consumption in the building sector. The aim of this endeavor is to comply with the standards prescribed by international treaties, such as the Kyoto Protocol and the Paris Agreement (2015) for greenhouse gas reduction. This trend implies that the new build housing units are likely less influenced by ambient $PM_{2.5}$ than are aged buildings with relatively leaking envelopes.

DISCUSSION

This study demonstrated that the infiltration test procedure employed was useful to assess the infiltration factors in

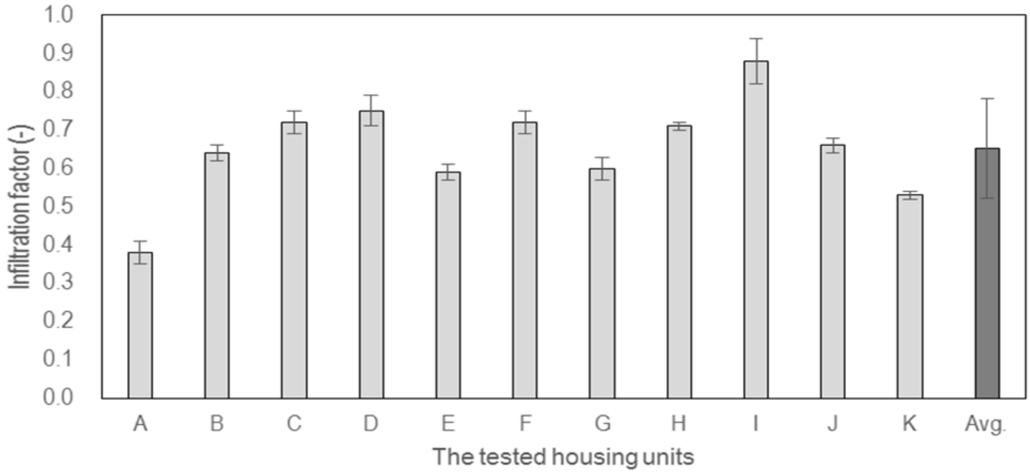

Fig. 4. $PM_{2.5}$ infiltration factors in test housing units.

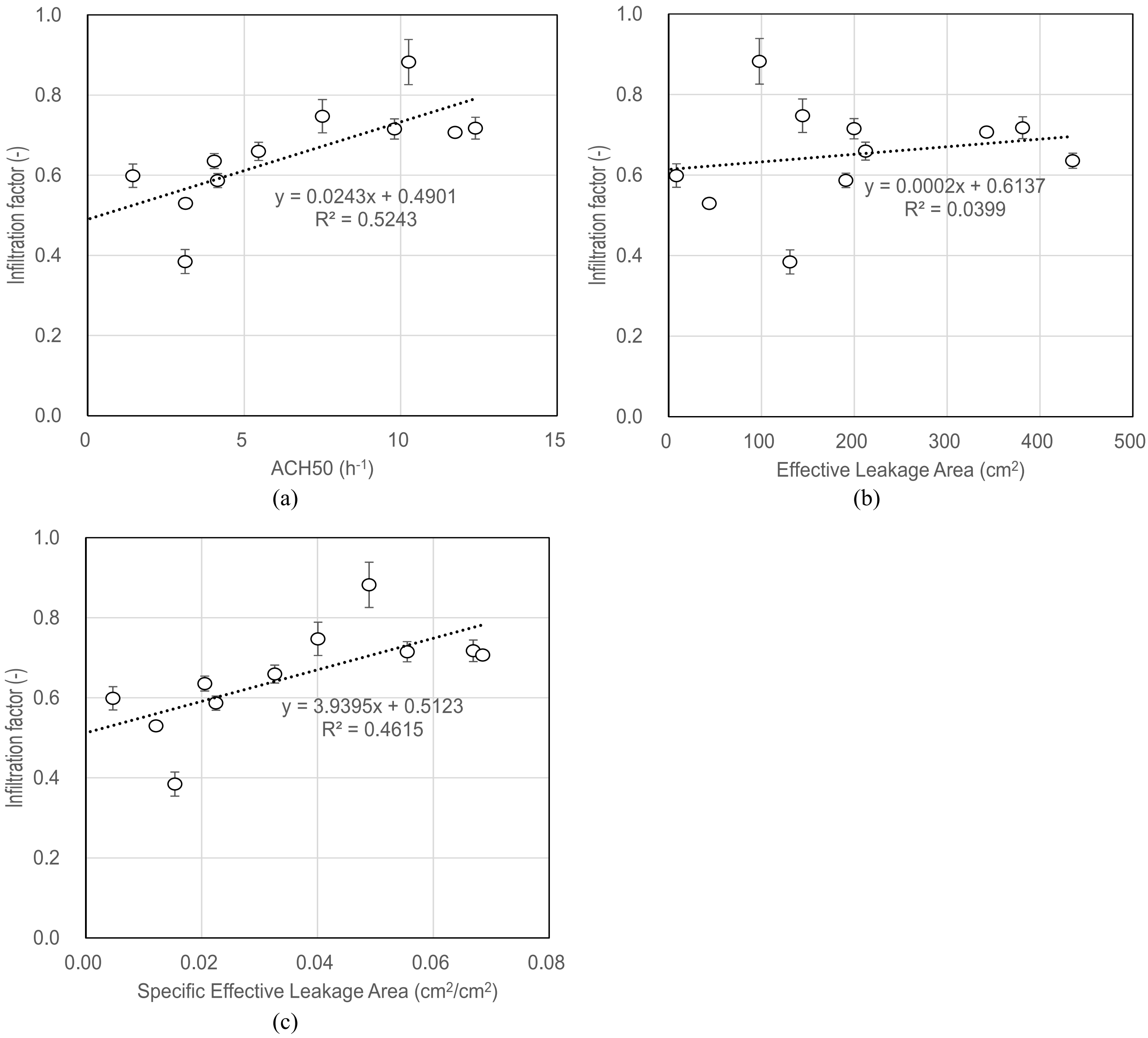

Fig. 5. Relationship of infiltration factors to airtightness test results: a) ACH_{50}; b) Effective leakage area (ELA); c) Specific effective leakage area (sELA).

conditions of controlled indoor-outdoor pressure difference in real housing units. The vertical distribution of pressure on the exterior wall of a high-rise multi-family house, similar to those often constructed in urban areas in Asian countries, would vary, depending on the wind pressure and stack effect. The suggested particle infiltration test method enabled direct comparison of the infiltration factors in all the test housing units, with the same pressure condition.

It should be noted that the infiltration factors were estimated in a pressure difference condition of 10 Pa between the indoor and the outdoor. Generally, it is known that the normal pressure difference applicable to a building envelope is 0 to 5 Pa. The slightly higher pressure difference in this study was intended to reduce the uncertainty of the infiltration tests. In numerous Asian cities, where high-rise residential buildings are abundant, the indoor-outdoor pressure difference would be larger than 5 Pa because of the wind and stack effect. Especially in winter, when the ambient $PM_{2.5}$ shows high levels because of industrial/domestic heating and dust events, the stack effect, combined with the outdoor wind velocity, would increase the pressure difference. Therefore, the 10 Pa difference test condition used in this study could be meaningful to indicate the impact of ambient $PM_{2.5}$ in indoor environments in such conditions. In real buildings, the direction of air flow and $PM_{2.5}$ transport would vary depending on the pressure conditions applied to building envelope resulting in different I/O ratios and infiltration factors. Further investigation of the influence of various pressure differences is being planned in future research.

Additionally, apartment housing units with no mechanical ventilation systems were investigated in this study; however, mechanically ventilated housing units would have different infiltration characteristics. Since 2009 in Korea, new build or remodeled apartment complexes with more than 100 units have been adopting mechanical ventilation systems in an effort to meet the level of 0.5 ACH specified for indoor air quality (IAQ). The effect of ambient $PM_{2.5}$ on the indoor environment in mechanically ventilated housing units should be examined in further study.

CONCLUSIONS

The current study investigated the infiltration of ambient $PM_{2.5}$ through the building envelop in apartment housing units in Korea. The on-site infiltration test method, by using a blower-door depressurization procedure, was used in order to maintain identical indoor-outdoor pressure differences among all the tests. On-site experiments in 11 apartment housing units were conducted to estimate the $PM_{2.5}$ infiltration factors. The results showed that the average infiltration factor of all the test housing units was 0.65 ± 0.13 (average ± standard deviation), with a minimum of 0.38 to a maximum of 0.88. In addition, the results from the relationship between the building airtightness data and the infiltration factors indicated that a leaky housing unit, with high ACH50 or high specific ELA, would be significantly more influenced by ambient $PM_{2.5}$. This study demonstrated that the infiltration test procedure suggested in this study was useful to assess the infiltration factors, in controlled indoor-outdoor pressure differences, in real housing units.

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